Achieving and Optimizing Separation of Magnetic Carriers from Pulsatile Blood Flow

Haitao Chen,[1] Axel J. Rosengart,[2,3] Michael D. Kaminski,[2,4] Patricia L. Caviness,[1] Carol J. Mertz,[4] Viji Balasubramanian,[1] Armin D. Ebner,[5] James A. Ritter[5]

[1]Department of Biomedical Engineering, Illinois Institute of Technology, Chicago, IL; [2]Co-Principal Investigator; [3]Neurocritical Care and Acute Stroke Program, Departments of Neurology and Surgery (Neurosurgery), The University of Chicago, Pritzker School of Medicine, Chicago, IL; [4]Chemical Engineering Division, Argonne National Laboratory, Argonne, IL; [5]Chemical Engineering Department, University of South Carolina, Columbia, SC;
[5]Chemical Engineering Department, University of South Carolina, Columbia, SC;

Overall Research Goal

Development, design, and demonstration of a magnetic filter to remove toxin-loaded magnetic particles. The overall detoxification system is being developed by Argonne National Laboratory and the The University of Chicago for selective and rapid removal of biological, chemical, and radioactive biohazards from humans.

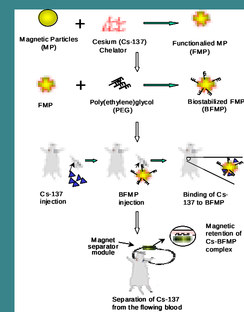
Current Detoxification Methods and Limitations

Hemodialysis and hemofiltration, plasmapheresis, extracorporeal immunoabsorption and direct injection of chelators and antibodies (immunotherapy) are the clinical methods currently used for blood detoxification (i.e., in kidney failure, autoimmune diseases, etc). However, **most blood-borne toxins cannot be removed with any of these methods** and they require a hospital setting, are generally of long duration, use extracorporeal circulation of large blood volumes, and—importantly--have non-selective substance removal limited to hydrophilic substances of low molecular weight.

Technical Summary of the Proposed System

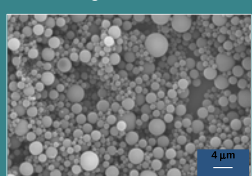
Conceptual rendition of proposed biotoxin detoxification technology. An exposed soldier self-administers magnetic nanoparticles and a strap-on magnetic filtration unit is attached by vascular access to an arm to remove the toxin. The magnetic filter must be designed to separate magnetic particles from pulsatile blood flow.

Method Exemplified by Cesium-137 Detoxification

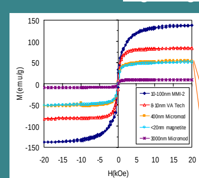


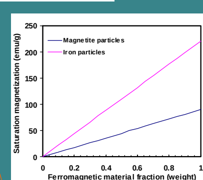
Magnetic Carriers

Magnetic Carriers



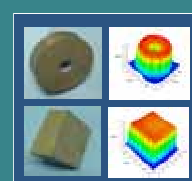
High-Magnetization Particles

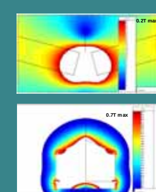




We use 400-nm magnetic carriers in which the magnetite content is 55% (w/w) and whose saturation magnetization is about 50 emu/g, as shown in the figure at left. Iron nanospheres can greatly improve magnetization (right).

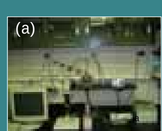
Magnetic Field Designs



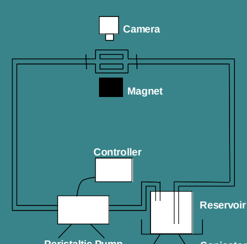


Need
- Strong magnetic field and field gradients over the length of tubing
- Strong fields near magnet surface
- Strong gradients near edges (fringe effect)

Magnetic Separation of Free-Flowing Magnetic Carriers

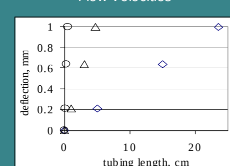


(a) Experimental apparatus for studying magnetic sphere liquid-suspension behavior under the influence of magnetic fields. (b) Digital camera used in the experiment.



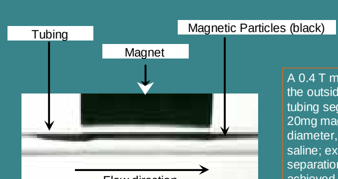
Multiple tubes will be applied at the magnetic separation area. The number of tubes can be from 2 to more than 20, depending on local blood velocity and other system parameters.

Nanosphere Trajectory at Various Flow Velocities



Simplified *in-vitro* flow model showing nanosphere trajectory at various flow velocities (◊=50 cm/s, Δ=10 cm/s, o=1 cm/s). Magnetic nanospheres, 400 nm diameter (measured moment 50 emu/g, density 1.4 g/cm^3) was contained in 0.9% saline in a 0.6-cm-diameter vial. A magnet (0.4 T at surface) was placed against the outside wall of the vial.

Separation of Magnetic Carriers



A 0.4 T magnet (NdFeB) placed against the outside of a short capillary glass tubing segment (inner diameter 1.2 mm); 20mg magnetic particles (7 µm in diameter, 20 emu/g) in 100 mL of 0.9% saline; excellent trapping and sphere separation from the circulating fluid was achieved for the tested flow velocities.

Flow Model

- 50% removal is available at a flow of 42 cm/s for one pass.
- To achieve 99% removal of the magnetic carriers, we needed to pass the tubing through the magnetic field seven times.
- To achieve a better removal for one pass in a pre-defined flow system, we can use an optimized magnetic field and a magnetic carrier with higher saturation magnetization.

Conclusions

- *In vitro* flow model demonstrated the feasibility of magnetic trapping and sequestration of free-flowing magnetic micro/nano spheres.
- Successful *in vivo* sequestration of magnetic spheres in large and smaller arterial branches after arterial upstream and systemic venous injection was also preliminarily identified.
- These findings directly support the design and development of a companion, compact magnetic filtration system, which will be useful in our proposed detoxification system for selective and rapid removal of biological, chemical, and radioactive biohazards from humans.

Funding for this work provided by U.S. Department of Defense, Defense Advanced Research Projects Agency, and The Cancer Research Foundation and The Brain Research Foundation of The University of Chicago

Argonne National Laboratory is operated by The University of Chicago for the U.S. Department of Energy

Collaborative Investigators for Applied Nanotechnology in Medicine